

36936000000052

**ACIDIC PRECIPITATION IN
SOUTH-CENTRAL ONTARIO:
ANALYSIS OF SOURCE REGIONS USING
AIR PARCEL TRAJECTORIES**

May, 1980

QH
545
.A17
K87
1980



Ontario

Ministry
of the
Environment

The Honourable
Harry C. Parrott, D.D.S.,
Minister

Graham W. S. Scott, Q.C.,
Deputy Minister

Copyright Provisions and Restrictions on Copying:

This Ontario Ministry of the Environment work is protected by Crown copyright (unless otherwise indicated), which is held by the Queen's Printer for Ontario. It may be reproduced for non-commercial purposes if credit is given and Crown copyright is acknowledged.

It may not be reproduced, in all or in part, for any commercial purpose except under a licence from the Queen's Printer for Ontario.

For information on reproducing Government of Ontario works, please contact Service Ontario Publications at copyright@ontario.ca

ACIDIC PRECIPITATION IN SOUTH-CENTRAL ONTARIO:

ANALYSIS OF SOURCE REGIONS USING AIR PARCEL TRAJECTORIES

J. Kurtz

Air Quality and Meteorology Section

Air Resources Branch

W. A. Scheider

Limnology and Toxicity Section

Water Resources Branch

May, 1980

Abstract

Measurements of precipitation pH, SO_4^{-2} and NO_3^- were taken from August 1976 to April 1979 in the Muskoka-Haliburton region of Ontario. Sea level geostrophic trajectories were used to follow the air mass associated with the event back 48 hours to its 'octant of origin'. Two types of data analysis were carried out, one using the entire data set (composite analysis) and one using only precipitation samples consisting of a single event (event analysis). Concentrations of H^+ , SO_4^{-2} and NO_3^- in event samples from the S, SW, W and NW octants were high. Results from the entire data set showed that precipitation events most commonly occurred with trajectories from the S and SW octants. Both event and composite analyses demonstrated that the majority of H^+ , SO_4^{-2} and NO_3^- deposited at Muskoka-Haliburton was associated with trajectories from the S and SW octants.

INTRODUCTION

The acidification of freshwaters by precipitation has occurred in Scandinavia (Oden 1976), the northeastern U.S.A. (Likens 1976, Schofield 1976) and the greater Sudbury area (Conroy et al. 1975, Beamish 1976). Recent evidence of acidic precipitation in south-central Ontario has been given by Dillon et al. (1978), who reported mean pH values of 3.95-4.38 at 8 sites in Muskoka-Haliburton. The dominant ions in precipitation at this site are H^+ and SO_4^{-2} and the deposition of H^+ and SO_4^{-2} is higher in Muskoka-Haliburton than at any other location on the Canadian Shield measured to date (Scheider et al. 1979a). Effects of acidic precipitation on the poorly buffered freshwaters of the area are discussed by Jeffries et al. (1979) and Scheider et al. (1979b).

In this paper, we attempt to relate the deposition and concentrations of H^+ , SO_4^{-2} and NO_3^{-1} in precipitation collected at Muskoka-Haliburton to pollution source regions through the use of air parcel trajectories. The rationale behind the study is to investigate the relative contributions from the various source regions in order to enable an assessment of proposed strategies aimed at controlling and reducing the acidity in Ontario's precipitation.

Trajectory analysis, to determine the sources of acidity in precipitation, has been applied in Sweden (Munn and Rodhe 1971), Norway (Forland 1973) and at sites in the northeastern U.S.A. (Dittenhoefer and Dethier 1976, Miller et al. (1978). Several authors have studied airborne SO_4^{-2} in Ontario and its relationship to long range transport (Lafleur and Whelpdale 1977, Chung 1978). Summers and Whelpdale (1976) related precipitation pH and SO_4^{-2} to air mass origin in a study performed in August 1976 in eastern Canada. To date, no longer term study has been carried out for this area. Here, we discuss the deposition and concentration of H^+ , SO_4^{-2} and NO_3^{-1} in precipitation collected at 5 sites in Muskoka-Haliburton over the period August 1976 - April 1979 with respect to air parcel trajectories.

DESCRIPTION OF STUDY AREA

Precipitation collectors were located in the Muskoka-Haliburton area of central Ontario (Figure 1). This area is underlain primarily by Precambrian bedrock with a thin, glacially derived overburden. A mixed deciduous/coniferous forest covers the area and no large urban or industrial centres exist within 200 kilometres.

METHODS

Precipitation was collected from August 1976 to April 1979 (33 months) at five sites using automatic, moisture-activated samplers. The samplers opened only during a precipitation event and thus excluded any dry deposition. The periods of collector operation are summarized in Figure 2. One sampler (Dorset) was electrically heated for winter use and snow samples were thus melted and kept in the liquid state. Rainfall depth was measured at each site using a 10 cm diameter polycarbonate rain gauge. The depth of snowfall was measured in 1978-79 with a Nipher snow gauge. In previous years, snow samples were melted and their volume measured to obtain water equivalent depths of snowfall. All precipitation gauges and collectors were located in cleared areas about 1m above ground (or snow) level. Samples were analyzed for pH and NO_3^{-1} within two days of collection. Analysis of SO_4^{-2} was performed in Toronto within one week of collection. Analytical methods are described in Ontario Ministry of the Environment (1975).

To trace the origin of the air associated with a precipitation event, we have used sea level geostrophic trajectories (Rossby and Egner 1955, Munn and Rodhe 1971, Forland 1973), computed from maps of the surface pressure field. A trajectory segment is derived for each six hourly surface map with the aid of a sea level geostrophic wind scale which provides the length and direction of the trajectory as a function of isobar spacing and orientation. The air parcel is followed back 48 hours in 6 hour increments to its 'octant of origin'. In some cases, the air mass associated with an event remained almost stationary for the 48 hours preceding the event. Such cases were termed 'local'.

Figure 1: Location of Study Area and Collectors. (Numbers refer to Figure 2)

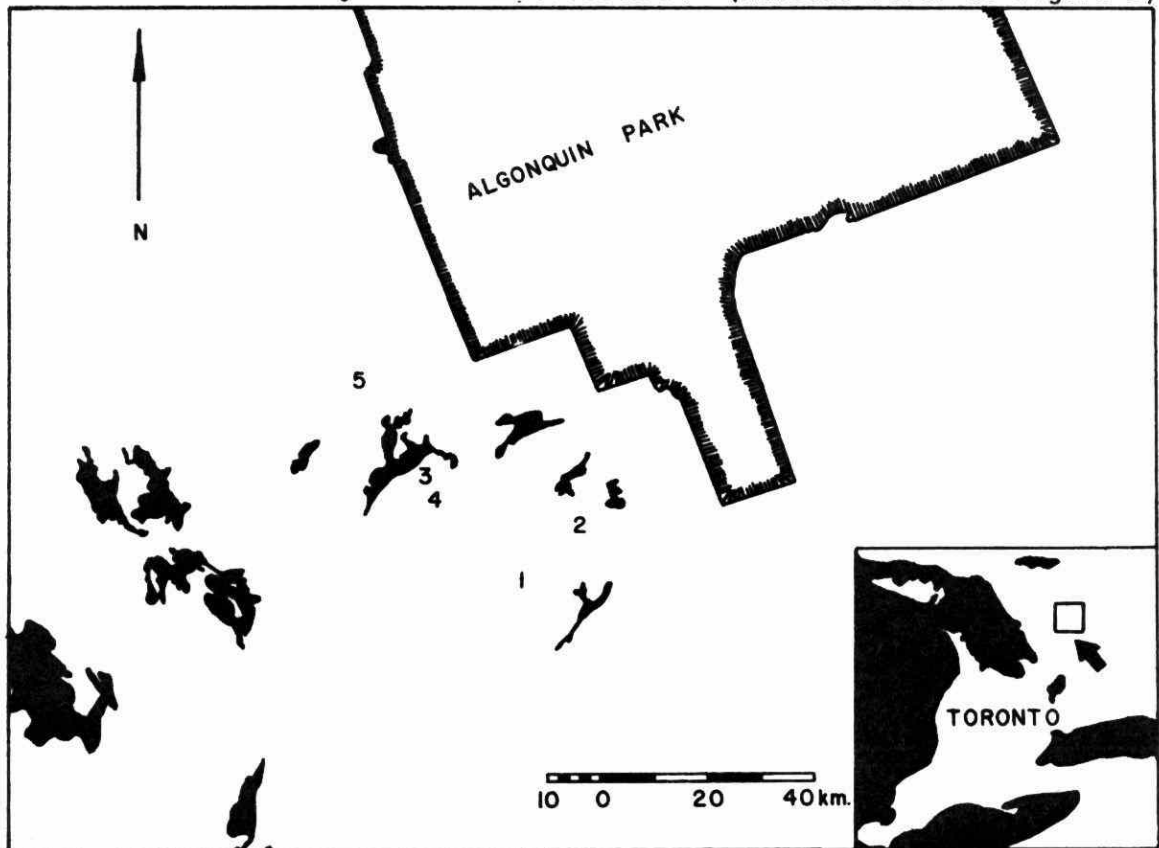
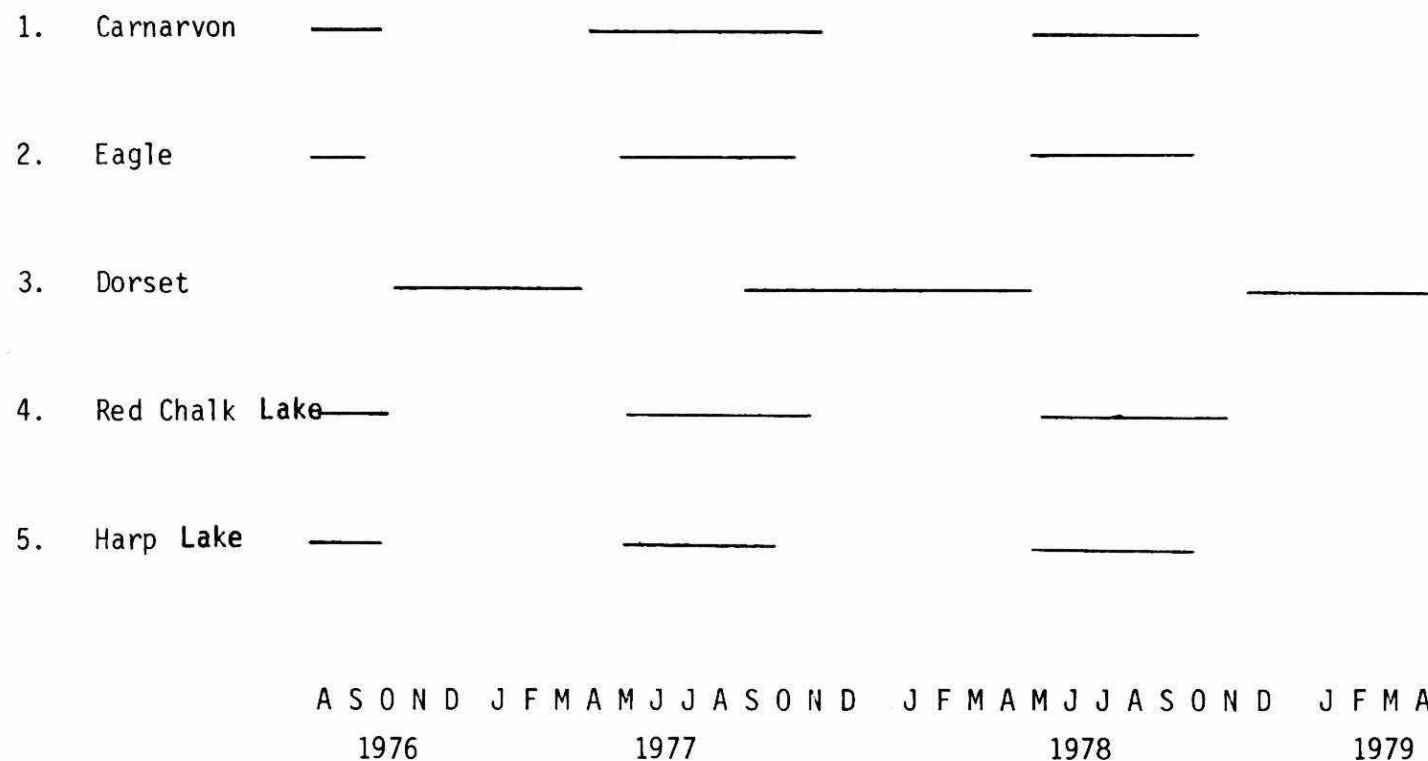


Figure 2: Periods of collector operation. Numbers refer to location on Figure 1.



The precipitation collectors are part of a network designed with the intent of calculating the bulk and wet deposition of nutrients, ions and heavy metals to lakes in the Muskoka-Haliburton area (Scheider et al. 1979 a, Jeffries and Snyder in press). For this reason, precipitation samples were collected when sufficient volume of sample existed for complete analysis. Depending upon the depth of precipitation in an event, one or several events may have contributed to a single sample.

In this study, we carried out two sets of computations - one for the entire data set (composite sample analysis) and one for samples consisting of a single precipitation event, or several events each associated with the same octant (event sample analysis). A summary of the number of measurements within the composite and event data sets is given in Table 1.

(a) Composite Sample Analysis

The composite data set consists of all data available, including that from composite collections in which several events contributed to the sample. We used these data to make estimates of the maximum possible deposition (of H^+ , SO_4^{-2} and NO_3^{-1}) which could correspond to each octant. Considering each octant in turn, we summed all of the sample loadings associated even partially with that octant. In generating maximum possible deposition we were assuming that events from the octant of interest alone contributed the total load to the sample.

An example may serve to clarify the procedure. Table 2A provides a data sample for the Red Chalk Lake station. To calculate the maximum possible H^+ loadings for each of the octants we get $1983 + 1085 = 3068$ for South, 3315 for South-East, 3315 for South-West, 3315 for North-West and 1085 for North-East (Table 2B). In the analysis, this procedure was applied to the H^+ , SO_4^{-2} and NO_3^- data for each station.

TABLE 1: Number of Measurements in Composite and Event Data Sets

<u>Station</u>	<u>Carnarvon</u>	<u>Dorset</u>	<u>Eagle</u>	<u>Harp Lake</u>	<u>Red Chalk Lake</u>
<u>Parameter</u>					
H ⁺ composite	54	56	53	37	40
SO ₄ ⁻² composite	47	34	50	38	34
NO ₃ ⁻¹ composite	40	37	40	38	30
depth-composite	60	58	61	44	43
H ⁺ event	27	24	28	20	18
SO ₄ ⁻² event	29	15	30	21	14
NO ₃ ⁻¹ event	21	16	24	20	11
depth-event	33	26	35	24	18

Table 2A: A data sample for the Red Chalk Lake Station (1978)

Collection Period	Depth (mm)	Sample pH	No. of Events	Octant(s) of origin	H ⁺ load (ueq m ⁻²)
Sept. 11-15	24.4	4.09	2	S, S	1983
Sept. 15-22	43.7	4.12	3	SE,SW,NW	3315
Sept. 22-29	11.1	4.01	2	NE, S	1085

Table 2B: Calculation of Maximum Possible H⁺ Loading for various octants of trajectory origin (based on data from Table 2A)

S	1983 + 1085 = 3068 ueq/m ²
SE	3315
SW	3315
NW	3315
NE	1085

As Figure 2 indicates, sampling at the Dorset station generally covered the cold months ('winter') while precipitation collectors at the remaining sites were made during the warm ('summer') months. We have therefore grouped the data into 'summer' (using the arithmetic mean of loadings at Carnarvon, Eagle Red Chalk Lake and Harp Lake) and 'winter' (using the Dorset loadings).

b) Event Sample Analysis

A second set of computations was based on the 'event' data i.e., those derived from precipitation collections consisting of a single precipitation event, or several events each associated with the same octant of origin. Initially, we computed total event loadings analogous to the composite loadings described above. We then computed weighted average concentrations for each octant and for each ionic constituent. The weighted average concentration is calculated from:

$$W_a = \frac{\sum_{i=1}^n \left(\sum_{j=1}^{m_i} L_{ij} / m_i \right)}{\sum_{i=1}^n \left(\sum_{j=1}^{m_i} d_{ij} / m_i \right)}$$

where: W_a = weighted average concentration for Octant "a"

L_{ij} = loading from collector j for event i

m_i = number of collectors or gauges operating for the i-th event

n = number of events corresponding to Octant "a"

d_{ij} = depth from gauge j for event i

RESULTS AND DISCUSSION

The limitations of this analysis are initially stated. They include:

- I. The majority of the precipitation collected is in the form of composite samples i.e., samples comprising two or more precipitation events. The value of such data to trajectory studies is limited (see, for example, Miller et al. 1978).

2. The size of the data set for event samples (i.e., those associated with a single precipitation event) is small. There are, for example, only one 'winter' and one 'summer' event sample corresponding to a trajectory from the northwest sector. The average concentrations associated with the less frequent sectors cannot be considered reliable.
3. The characterization of acidic precipitation events using a single trajectory may be misleading as (a) the storm system involves inflow of air from many directions through convergence in the vicinity of the cyclonic cell, and (b) the mechanism of acidic precipitation formation is a complex amalgam of rainout and washout processes occurring at many atmospheric levels possessing different directions of air flow. Despite these difficulties, some success has been reported from the use of trajectories for tracing source regions (e.g., Forland 1973, Nordo 1975 and Wisniewski 1976).

Table 3 shows the percentage precipitation event samples associated with each octant of trajectory origin as compared with the percentage of composite samples associated with each octant of origin, for the H^+ data set. (The SO_4^{-2} and NO_3^{-1} data sets show qualitatively similar distributions). The Table shows that the South and South-West trajectory directions are more frequent in the event data set while several other trajectory directions are less frequent (particularly East, South-East and North-West). This difference in the frequency distribution results in a corresponding difference in the computed loadings of H^+ , SO_4^{-2} and NO_3^{-1} by octant of origin.

The results of the composite sample analysis (Table 4) show the maximum possible deposition of H^+ , SO_4^{-2} and NO_3^{-1} which could correspond to each octant of trajectory origin. In the case of each of the constituents, and both warm and cold seasons, the South and South-West octants are associated with the greatest

TABLE 3: Percentage of precipitation samples, on which H⁺ analysis was done, associated with each octant of trajectory origin for event and composite data sets

<u>Octant of Origin</u>	<u>Summer*</u>		<u>Winter</u>	
	<u>Event Data (%)</u>	<u>Composite Data (%)</u>	<u>Event Data (%)</u>	<u>Composite Data (%)</u>
NE	5	6	4	7
E	0	4	4	7
SE	0	6	0	8
S	25	19	42	22
SW	46	29	34	24
W	14	13	4	13
NW	2	7	4	9
N	1	3	8	6
Local	7	7	0	4
Number of Samples	18-28	37-54	24	56

* Mean Frequencies for 4 stations are tabulated.

Table 4: Maximum Possible Loadings of H^+ , SO_4^{-2} and NO_3^{-1} ($meq\ m^{-2}$) Associated with Octants of Trajectory Origin (based on composite sampling data, Aug. 1976-April 1979)

		Summer*		Winter	
		(meq/m^2)	(%)	(meq/m^2)	(%)
H^+	NE	4	6	34	32
	E	7	10	28	26
	SE	7	10	16	15
	S	26	37	42	40
	SW	35	50	60	57
	W	15	21	27	25
	NW	10	14	32	30
	N	3	4	4	4
	Local	7	10	13	12
	Total**	70	162	106	241
SO_4^{-2}	NE	6	9	14	29
	E	5	7	14	29
	SE	5	7	9	18
	S	23	33	25	51
	SW	34	49	31	63
	W	15	21	15	31
	NW	8	11	12	24
	N	3	4	0.4	1
	Local	10	14	4	8
	Total**	70	155	49	254
NO_3^{-1}	NE	2	7	9	30
	E	2	7	9	30
	SE	2	7	4	13
	S	11	38	13	43
	SW	12	41	18	60
	W	6	21	7	23
	NW	3	10	10	33
	N	0.4	1	1	3
	Local	6	21	1	3
	Total**	29	153	30	238

*mean of 4 stations

** The total load is not the sum of the individual octant loadings (see text).
Total % figures shown are calculated from total loadings shown.

maximum possible deposition and the North octant is associated with the lowest maximum possible deposition.

No more than 10% (and likely much less) of the 'summer' deposition of H^+ , SO_4^{-2} and NO_3^{-1} could be associated with any of the N, NE, E and SE octants. From the 'winter' analysis only the North octant was associated with less than 10% of the deposition of each of the constituents. However, the 'winter' figures are less reliable than the 'summer' values because of the greater number of events per collection which is reflected in the larger sum of % values (Table 4).

The results of the event sample analysis (Table 5), although based on a smaller data set, give an estimate of the % of total deposition contributed per octant of origin. In the 'summer' period, events originating in the S and SW octants combined contributed 75% of the H^+ , 70% of the SO_4^{-2} and 57% of the NO_3^{-1} deposition. 'Local' events contributed 10%, 16% and 27% of the H^+ , SO_4^{-2} and NO_3^{-1} respectively. Events originating in the W octant contributed 9%, 8% and 10% of the H^+ , SO_4^{-2} and NO_3^{-1} deposition. Events from all other octants contributed 2% or less per octant of the total deposition. In the 'winter' period, events from S and SW octants again were most important, depositing 85%, 87% and 86% of the H^+ , SO_4^{-2} and NO_3^{-1} respectively. The fraction of the total load deposited by events from the W octant dropped to less than 5% and events from the 'local' sector contributed 0%.

Basically, both data sets show a similar result i.e. that most of the deposition of H^+ , SO_4^{-2} and NO_3^{-1} was probably associated with events originating in the S and SW octants. The W and 'local' sectors were also important contributors to the total deposition in the 'summer' months.

Our results agree with those of Summers and Whelpdale (1976) and Whelpdale (1978) who reported elevated levels of SO_4^{-2} and H^+ in precipitation falling in southern Ontario to be associated with southerly flows of air. Indirect

TABLE 5: Sampled Loadings of H^+ , SO_4^{-2} and NO_3^{-1} (meq m^{-2})
Associated With Octants of⁴ Trajectory Origin (based on event sampling
data, Aug. 1976 - April 1979)

		<u>Summer*</u>		<u>Winter</u>	
		(meq/m^2)	%	(meq/m^2)	%
H^+	NE	0.8	2	1.4	5
	E	0.0	0	0.1	0
	SE	0.0	0	0.0	0
	S	11.0	33	12.6	45
	SW	14.1	42	11.3	40
	W	2.9	9	0.8	3
	NW	0.6	2	1.5	5
	N	0.8	2	0.5	2
	Local	3.4	10	0.0	0
	Total	33.6	100	28.2	100
SO_4^{-2}	NE	0.9	2	0.7	5
	E	0.0	0	0.0	0
	SE	0.2	1	0.0	0
	S	12.5	31	2.9	21
	SW	15.6	39	9.0	66
	W	3.4	8	0.5	4
	NW	0.7	2	0.2	1
	N	0.6	1	0.4	3
	Local	6.5	16	0.0	0
	Total	40.4	100	13.7	100
NO_3^{-1}	NE	0.2	1	1.1	13
	E	0.0	0	0.0	0
	SE	0.1	1	0.0	0
	S	4.9	30	3.5	40
	SW	4.5	27	4.0	46
	W	1.6	10	0.0	0
	NW	0.3	2	0.1	1
	N	0.3	2	0.0	0
	Local	4.6	27	0.0	0
	Total	16.5	100	8.7	100

*mean of 4 stations

support comes from Lafleur and Whelpdale (1977) and Chung (1978), who concluded from Ontario data that elevated levels of SO_4^{-2} in air measured by high-volume samplers were associated with S-SW air flows. At Ithaca, N.Y. some 350 km south-east of Muskoka-Haliburton, Cogbill and Likens (1974), Dittenhoeffer and Dethier (1976) and Miller et al. (1978) all reported that precipitation originating in the SW sector was the most acidic. Wolff et al. (1979) found for New York, N.Y. that events originating in the W and SW sectors had the lowest pH values. Samson (1978) reported that the highest SO_4^{-2} levels in air collected with high-volume samplers at three locations in New York were associated with air parcels from the SW octant. Many studies point to the highly populated, industrialized S and SW sectors as being the major source areas of polluted air, a reflection of the greater strength of sources in these directions (see, for example, Clark 1978).

Table 6 is a tabulation of weighted average concentrations for H^+ , SO_4^{-2} , and NO_3^{-1} , based on the event data set. Weighted average concentrations serve to characterize the precipitation associated with various source regions. Comments on the Table cannot be too extensive due to the relatively small sample size. For example, the very high average concentrations for H^+ in 'winter' corresponding to E and NW trajectories are based on isolated events. Much more event data are needed before meaningful conclusions can be drawn. It should be noted, however, that a significant concentration of each of the 3 ionic species characterizes precipitation associated with the S, SW, W and NW directions. Note also that the weighted average concentrations in 'summer' are relatively high for 'local' events. This circumstance is possibly due to inflow of air from the Sudbury region (200 km north-west of Muskoka-Haliburton) associated with slow moving storms.

TABLE 6: Weighted Average Concentrations of H^+ , SO_4^{-2} and NO_3^{-1} (ueq/l) (based on event sampling data, Aug. 1976 - April 1979)

		<u>Summer*</u>		<u>Winter</u>	
		ueq/l	number of events	ueq/l	number of events
H^+	NE	36	3	43	1
	E	-	0	204	1
	SE	-	0	-	0
	S	81	11	89	10
	SW	70	18	69	8
	W	101	7	102	1
	NW	106	1	229	1
	N	81	1	17	2
	Local	83	4	-	0
SO_4^{-2}	NE	41	3	21	1
	E	-	0	-	0
	SE	21	1	-	0
	S	81	10	38	4
	SW	93	19	55	7
	W	73	5	63	1
	NW	114	1	23	1
	N	58	1	21	1
	Local	138	4	-	0
NO_3^{-1}	NE	13	2	32	1
	E	-	0	36	1
	SE	6	1	-	0
	S	35	8	30	7
	SW	31	15	48	6
	W	45	5	-	0
	NW	53	1	14	1
	N	29	1	-	0
	Local	91	3	-	0

*mean of 4 stations

CONCLUSIONS

In summary:

- (i) precipitation events most commonly occur with trajectories from the South and South-West octants,
- (ii) an analysis of both composite and event data sets for the 33-month period shows that the majority of H^+ , SO_4^{-2} and NO_3^{-1} deposited at Muskoka-Haliburton is associated with trajectories from the South and South-West, and
- (iii) the average concentrations of H^+ , SO_4^{-2} and NO_3^{-1} in precipitation for the S, SW, W and NW octants are all substantial; precipitation from the remaining octants was very infrequent.

Acknowledgments

We would like to thank W.R. Snyder, B. Clark and R.A. Reid for their assistance in the field. Chemical analyses were carried out by C. Chun and N. Nicolls in Dorset and by staff of the Water Quality Section, Laboratory Services Branch in Toronto. We thank P.J. Dillon and L. Shenfeld for their comments on the manuscript. This study was funded by the Lakeshore Capacity Study and the Acidic Precipitation in Ontario Study.

REFERENCES

- BEAMISH, R.J. (1976). Acidification of lakes in Canada by acid precipitation and the resulting effects on fishes. *Water Air Soil Pollut.* 6, 501-514.
- CHUNG, Y.S. (1978). The distribution of atmospheric sulphates in Canada and its relationship to long-range transport of air pollutants. *Atmospheric Environment* 12, 1471-1480.
- CLARK, T.L. (1978). Gridded Pollutant Emissions in the U.S. and southern Canada East of the Rockies. Presented at the 71st Annual meeting the Air Pollution Control Association, Houston, Texas, June 25-30, 1978.
- COGBILL, C.V. and LIKENS G.E. (1974). Acid precipitation in the northeastern United States. *Water Resour. Res.* 10, 1133-1137.
- CONROY, N., HAWLEY, K., KELLER, W. AND LAFRANCE, C. (1975). Influence of the atmosphere on lakes in the Sudbury area. *Proc. 1st Spec. Symp. on atmospheric contributions to the chemistry of lake waters. Int. Assoc. Great Lakes Res.* 146-165.
- DILLON, P.J., JEFFRIES, D.S., SNYDER, W., REID, R., YAN, N.D., EVANS, D., MOSS, J. AND SCHEIDER, W.A. (1978). Acidic precipitation in south-central Ontario: recent observations. *J. Fish. Res. Bd. Canada* 35, 808-815.
- DITTENHOEFER, A.C. and DETHIER, B.E. (1976). The precipitation chemistry of western New York state: a meteorological interpretation. Office of Water Research and Technology, U.S. Dept. of the Interior.
- FORLAND, E.J. (1973). A study of the acidity of the precipitation in south-western Norway. *Tellus* 25, 291-298.
- JEFFRIES, D.S., COX, C.M. AND DILLON, P.J. (1979). Depression of pH in lakes and streams in central Ontario during snowmelt. *J. Fish. Res. Bd.* 36, 640-646.

- JEFFRIES, D.S. AND SNYDER, W.R. (in press). Concentrations and deposition of heavy metals in precipitation in central Ontario. (Water, Air and Soil Pollution).
- LAFLEUR, R.J. and WHELPDALE, D.M. (1977). Spatial distribution of sulphates over eastern Canada during August 1976. Presented at the 70th Annual Meeting of the Air Pollution Control Assoc., Toronto, Ont., Canada, June 1977.
- LIKENS, G.E. (1976). Acid precipitation. Chem. Eng. News 54, 29-44.
- MILLER, J.M., GALLOWAY, J.N. AND LIKENS, G.E. (1978). Origin of air masses producing acid precipitation at Ithaca, New York. Geophysical Research Letters 5, 757-760.
- MUNN, R.E. and RHODE, H. (1971). On the meteorological interpretation of the chemical composition of monthly precipitation samples. Tellus 23, 1-12.
- NORDO, J. (1975). Long range transport of air pollutants in Europe and acid precipitation in Norway. in Proceedings of the First International Symposium on Acid Precipitation, Columbus, Ohio, pp. 87-103.
- ODEN, S. (1976). The acidity problem - an outline of concepts. Water Air Soil Pollution 6, 137-166.
- ONTARIO MINISTRY OF ENVIRONMENT (1975). Outline of analytical methods. Ontario Ministry of the Environment, 130pp.
- ROSSBY, C.G. and EGNER, H. (1955). On the chemical climate and its variation with the atmospheric circulation pattern. Tellus 7, 118-133.
- SAMSON, P.J. (1978). Ensemble trajectory analysis of summertime sulfate concentrations in New York State. Atmospheric Environment 12, 1889-1893.

- SCHEIDER, W.A., SNYDER, W.R. AND CLARK, B. (1979 a). Deposition of nutrients and major ions by precipitation in south-central Ontario. *Water Air Soil Pollution* 12, 171-185.
- SCHEIDER, W.A., JEFFRIES, D.S. and DILLON, P.J. (1979 b). Effects of acidic precipitation on precambrian freshwaters in southern Ontario. *J. Great Lakes Res. Internat. Assoc. Great Lakes Res.* 5, 45-51.
- SCHOFIELD, C.L. (1976). Acid precipitation: effects on fish. *Ambio* 5, 228-230.
- SUMMERS, P.W. and WHELPDALE, D.M. (1976). Acid precipitation in Canada, *Water Air Soil Pollution* 6, 447-455.
- WHELPDALE, D.M. (1978). Large-scale atmospheric sulphur studies in Canada. *Atmospheric Environment* 12, 661-670.
- WISNIEWSKI, J. (1976). Variability of rainwater silver concentration in South Florida. in *Proceedings of the International Weather Modification Conference*, Boulder, Colorado, 5 pp.
- WOLFF, G.T., LIOY, P.J., GOLUB, H. and HAWKINS, J.S. (1979). Acid precipitation in the New York Metropolitan area: its relationship to meteorological factors. *Environmental Science and Technology* 13, 209-212.

QH
545
.A17
K87
1980